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Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1

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Abstract

Purpose Sustainability Science (SS) is considered an emerging discipline, applicative and solution-oriented whose aim is to handle environmental, social and economic issues in light of cultural, historic and institutional perspectives. The challenges of the discipline are not only related to better identifying the problems affecting sustainability but to the actual transition towards solutions adopting an integrated, comprehensive and participatory approach. This requires the definition of a common scientific paradigm in which integration and interaction amongst sectorial disciplines is of paramount relevance. In this context, life cycle thinking (LCT) and, in particular, life cycle-based methodologies and life cycle sustainability assessment (LCSA) may play a crucial role. The paper illustrates the main challenges posed to sustainability assessment methodologies and related methods in terms of ontology, epistemology and methodology of SS. The aims of the analysis are twofold: (1) to identify the main features of methodologies for sustainability assessment and (2) to present key aspects for the development of robust and comprehensive sustainability assessment.

Methods The current debate on SS addressing ontological, epistemological and methodological aspects has been reviewed, leading to the proposal of a conceptual framework for SS. In addition, a meta-review of recent studies on sustainability assessment methodologies and methods, focusing those life cycle based, supports the discussion on the main challenges for a comprehensive and robust approach to sustainability assessment. Starting from the results of the meta-review, we identified specific features of sustainable development-oriented methods: firstly, highlighting key issues towards robust methods for SS and, secondly, capitalising on the findings of each review's paper. For each issue, a recommendation towards a robust sustainability assessment method is given. Existing limitations of sectorial academic inquiries and proposal for better integration and mainstreaming of SS are the key points under discussion.

Discussion In the reviewed papers, LCT and its basic principles are acknowledged as relevant for sustainability assessment. Nevertheless, LCT is not considered as a reference approach in which other methods could also find a place. This aspect has to be further explored, addressing the lack of multi-disciplinary exchange and putting the mainstreaming of LCT as a priority on the agenda of both life cycle assessment and sustainability assessment experts. Crucial issues for further developing sustainability assessment methodologies and methods have been identified and can be summarised as follows: holistic and system wide approaches, shift from

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multi- towards trans-disciplinarity; multi-scale (temporal and geographical) perspectives; and better involvement and participation of stakeholders.
Conclusions Those are also the main challenges posed to LCSA in terms of progress of ontology, epistemology and methodology in line with the progress of SS. The life cycle-based methodologies should be broadened from comparing alternatives and avoiding negative impacts, to also proactively enhancing positive impacts, and towards the achievement of sustainability goals.

Keywords Life cycle assessment · Life cycle sustainability assessment · Life cycle thinking · Science–policy interface · Sustainability assessment · Sustainability science

1 Introduction

A new paradigm for economic growth, social equality and environmental protection was set in 1987 when the 'Brundtland's report' (WCED 1987) introduced the concept of sustainable development to the international community. Since then, the world has gained a deeper understanding of the interconnected challenges we face and has recognised that sustainable development has to embrace several sustainability pillars: from the three fundamental pillars related to environmental, economic and social aspects to pillars concerning, e.g. institutional (O'Connor 2006), cultural (Nurse 2006) and technological (Vos 2007) ones. Sustainable development (SD) is not a destination, but a dynamic process of adaptation, learning and action. It is about recognising, understanding and acting on interconnections, above all those between the economy, the society and the natural environment. We cannot make lasting progress in one pillar without progress on all (UN 2012).

Within the scientific community, the definition of sustainability and 'what should be sustained' (e.g. what might constitute critical natural capital) is by no means agreed on and is subject to value judgements (Bell and Morse 2008; Bond et al. 2011), up to be interpreted as a shared ethical belief (Seager et al. 2004). SD is a complex concept, normative, subjective, entailing inter- and intra-generation aspects and can neither be unequivocally described nor simply applied. Schematically, four main interpretations of the concept of sustainability may be identified: (1) ecological, (2) economic, (3) thermodynamic and ecological–economic, and (4) public policy and planning theory (Patterson 2010). The ecological interpretation focuses on a vision of the socio-economic system embedded in the global biophysical system; the economic emphasises the idea of social welfare; the thermodynamic interpretation poses ecological sustainability in the context of the entropic nature of economic–environmental interactions; and the public policy and planning interpretation seeks to achieve a balance of the different aforementioned factors. Each of these interpretations implies a different scientific domain, with some knowledge areas overlapping and others diverging or overlooked.

Besides, the dynamic evolution and the complexity of the challenges posed by sustainability are hardly manageable in the context of classical disciplines and science (Hasna 2010; Bettencourt and Kaur 2011). Hence, Sustainability Science (SS) emerged as a revolutionary concept that, in the Kuhnian sense (Kuhn 1970), is aimed at providing a response to the crisis of present 'normal[1] sciences', enabling science to contribute more effectively to sustainable development through a holistic approach, able to capitalise and integrate sectorial knowledge towards the definition of new solutions. This area has become a scientific possibility for transcending reductionist analyses of classical sciences, by means of systemic comprehension of contemporary phenomena within the environmental, ecological, economic, social and political domains. SS is a discipline that aims at exploring the dynamic interactions between human activities on the Earth's life support systems, and between nature and society, to design a path towards sustainable development.

The basic questions of the discipline were defined by Kates et al. (2001), initiating the scientific debate about the emergence of SS. These core questions address the need of incorporating the dynamic interactions between nature and society, including lags and inertia, into models and conceptualisations of sustainability; the need to integrate the effects of key processes across the full range of scales from local to global; and the need to achieve fundamental advances in our ability to address such issues and govern multiple and interacting stresses (e.g. incentive structure, monitoring and reporting, adaptive management and societal learning).

An overview of issues to be tackled by SS has been recently published by the United Nations Secretary-General's High-level Panel on Global Sustainability in the report 'Resilient People, Resilient Planet: A future worth choosing' (UN 2012). The Panel's vision for a sustainable planet, a just society and a growing economy aims at eradicating poverty; reducing inequality and making growth inclusive; making production and consumption more sustainable, while combating climate change and respecting a range of other planetary boundaries; enabling consumers to make sustainable choices and to advance responsible behavior individually and collectively; managing resources and enabling a twenty-first century green revolution in the fields of agriculture, oceans and coastal systems, energy and technology.

[1] The term refers to the routine work of scientists experimenting within a paradigm, slowly accumulating detail in accordance with established broad theory, not actually challenging or attempting to test the underlying assumptions of that theory (Kuhn 1970).

Amongst the above-mentioned areas of intervention, the transition towards sustainable production and consumption is recognised as one of the major challenges for sustainability.

Specific methodologies are needed in order to analyse the present situation, to define future scenarios and to assess the capability of policies, plans and actions to provide adequate solutions.

In this context, life cycle thinking (LCT)—due to its systemic approach—is considered to provide a valuable support in integrating sustainability into design, innovation and evaluation of products and services. Evidence thereof is given in the numerous environmental policies at European (e.g. CEC 2004; CEC 2005; CEC 2008; CEC 2010; CEC 2011) and international level (e.g. UNEP 2004 and 2012) in which LCT represents the backbone. In fact, life cycle-based methodologies and in particular the life cycle assessment (LCA) are inherently rooted into SS at the conceptual level but still not fully integrated.

In the context of LCT, LCA represents an integrated methodology for environmental assessment, in which a wide number of scientific domains and expertise are involved. LCA is considered by some authors as the state of the art relating to the environmental dimension of sustainability, despite some limitations and unresolved issues in all the phases (see Reap et al. 2008a,b for details). This is based on the fact that LCA simply applies a linear static model based on technological and environmental relations in inventory and impact assessment phases, respectively, and it is moreover restricted to impacts on the environment (Heijungs et al. 2010). LCA essentially aims at making better informed decisions related to products and services in business and policy, providing evidence-based and comprehensive assessment. Actually, two LCA features are particularly relevant for addressing environmental sustainability: (1) the life cycle perspective, all phases ('from the cradle to the grave') of the life cycle of a product (good or service) are assessed with regard to all relevant material and energy flows, from the extraction and processing of the resources, production and further processing, distribution and transport, use and consumption to recycling and disposal; (ii) cross-media environmental approach in which relevant environmental impacts are taken into account, i.e. both on the input side (use of resources) and on the output side (emissions into air, water and soil, including waste and physical impacts) (EC-JRC 2010a; Guinée et al. 2002).

The question is whether the current development of LCT and life cycle-based methodologies [namely, life cycle costing (LCC), social life cycle assessment (sLCA) and life cycle sustainability assessment (LCSA)] are able to provide decision support in order to answer the key questions of sustainability posed by Kates et al. (2001) and to provide solutions to challenges such as those posed by UN (2012). Moreover, acknowledging the recent advancements in not only LCA but also LCC and sLCA and the development of LCSA framework,[2] it is paramount to discuss the extent to which life cycle-based methods are aligned with SS requirements.

Considering the current scientific debate on SS and related sustainability assessment (SA) methodologies and methods, we developed a series of two papers to identify, amongst the numerous points under discussion, the crucial elements for enhancing life cycle-based methodologies and for supporting the development of LCSA towards a mainstreaming of sustainability (namely, the integration of sustainability concepts and requirements in each aspects of the methodology). This paper focuses on three main questions:

- Which is the domain of sustainability science (ontology), i.e. what a sustainability assessment method should assess?
- Which are the epistemological foundations of SS, and how they influence the scientific paradigm and the related methodologies for the assessment?
- Which are the peculiarities of sustainability assessment methods and how LCA is perceived within the SS domain?

We attempt to answer these challenging questions by: (1) defining the main features of sustainability assessment methods and (2) presenting key aspects for the development of robust and comprehensive sustainability assessment methods.

The following approach has been adopted:

- The review of the points under discussion and the main challenges in the current debate on sustainability science (Section 2.1), addressing the main ontological (Section 2.2) and epistemological aspects (Section 2.3) of SS and proposing a conceptual framework of SS (Section 2.4)
- The assessment of the peculiarities of SA methodologies trough a meta review of papers comparing LCA amongst other SA methodologies, highlighting how current literature evaluates them and identifying underpinning key criteria for their robust and comprehensive development (Section 3)

The criteria are then used in the part II of this series of paper (Sala et al. 2012) to discuss current approaches to life cycle-based methodologies and LCSA in light of SS.

2 Sustainability science: from current status to the proposal of a conceptual framework

As stated in Section 1, SS has emerged as a new discipline, aimed to provide a response to the crisis of present normal sciences, enabling science to contribute more effectively to sustainable development through a holistic approach. The

[2] The LCSA framework consists of a combination of the three methods mentioned above.

following sections present the evolution of the discipline and the current debate on epistemological and ontological aspects.

As a result of the overview on the current status of SS, we proposed a conceptual framework for SS to systematise the knowledge area, and we define the terminology related to the discipline used within this paper.

2.1 The emergence of sustainability science

The inability of the so-called ‘normal sciences’ to tackle and provide solutions to the urgent complex problems that are arising as consequence of human–nature interactions, has pushed the scientific community to find new methodologies, methods, models and paradigms for reflecting the complexity and the multi-dimensional character of SD and has led to the emergence of the field of SS. SS embodies the scientific possibility of transcending the reductionist analyses of classical sciences by means of a systemic understanding of contemporary phenomena, both in economic and social spheres and in environmental, political and ecological areas (Osorio et al. 2009). As a new discipline (Kates et al. 2001; Clark and Dickson 2003; Komiyama and Takeuchi 2006), SS requires an established and coherent body of central features, which Kuhn would describe as fundamental properties that provide a basis for the initial practice of a newly established sphere of science (Kuhn 1970).

SS has been discussed since the 1990s (e.g. Costanza 1991), leading to a conceptualisation of the science as an advanced form of complex system analysis aimed at enhancing the understanding of the coupled human–environmental condition through advanced analytical–descriptive tools (Turner et al. 2003). The core questions defining the theoretical field of SS (Kates et al. 2001) focus on this understanding. As a problem- and solution-oriented field, SS has been classified in literature as an applied research or as use-inspired research (Stokes 1997; Clark and Dickson 2003), where the research trajectories are defined by the problems it aims at solving, or as transformational research (Wiek et al. 2012a), inter alia based on concepts of use-inspired-basic research, post-normal and mode-2 (Stokes 1997; Funtowicz and Ravetz 1993; Gibbons et al. 1994) that employs corresponding research practices, such as trans-disciplinary, community-based, interactive, or participatory approaches (Kasemir et al. 2003; Savan and Sider 2003; Robinson and Tansey 2006; Hirsch Hadorn et al. 2006; Jahn 2008; Scholz et al. 2006).

The above-mentioned practices have in common a new science–society interaction, leading to multiple forms of knowledge, synthesis of theory and practice to resolve pressing societal problems through the collaboration amongst scientists from different academic disciplines and with other stakeholder groups (business, government and civil society).

SS has been debated for over 20 years, but an agreed and univocal definition of what SS entails has not been formulated (e.g. Spangenberg 2011; Wiek et al. 2012a; Sterman 2012; van der Leeuw et al. 2012).

Being characterised more by its research purpose than by a common set of methodologies or objectives, SS can be subdivided into the more traditional disciplinary-based science for sustainability and the trans-disciplinary science of sustainability. Whereas the former consists of more descriptive, analytical and basic science, the latter is characterised by reflexivity and applicability (Spangenberg 2011). Therefore, the discipline is multi-faceted and any definition should consider that in current literature the emerging SS is characterised by the following main features:

– Focus on dynamic interactions between nature and society: the understanding of dynamic interactions, vulnerability and resilience (see further Section 2.2.3) of complex social–ecological systems at a systemic level requires a holistic approach and perception of reality. This is usually lacking in ‘normal’ science, where a specific focus is given, e.g. to separate biophysical aspects one at a time
– Transdisciplinarity approach: in order to assess, understand and find solutions to complex phenomena there is a need to bring together the different levels of knowledge of reality, under a reductionist or holistic view. The trans-disciplinary approach emerged as the most appropriate. Differently from multi-disciplinary (characterised by un-integrated application of more than one disciplinary methodology to analyse a topic from different perspectives, Wickson et al. 2006; Nicolescu 2000; Balsiger 2004) and inter-disciplinary approach (that integrates methods, concepts and theories, transferring them from one discipline to another to achieve a common understanding on complex problems (Wickson et al. 2006; Nicolescu 2000), trans-disciplinary approach is characterised by functional integration of different methodologies and epistemologies and co-production of knowledge through collaboration and participation of different stakeholders who have interests in the solution of complex problems such as sustainability related ones. It is also characterised by the strong link with the specific social/local context and institutional setting from where sustainability problems originate, the inclusion of all values and common goods perceptions in the identification of the solutions (subjective and normative dimensions); and its application in contexts different from those where they originate (Gibbons et al. 1994; Hirsch Hadorn et al 2008; Kasemir et al. 2003; Pohl 2008; Lang et al. 2012).
– Normative function (capability to provide direction through visions and goals): SS addresses the normative

question of how coupled human–environment systems would function and look in compliance with a variety of value-laden goals and objectives. Moreover, it addresses the strategic and operational questions of what viable transition pathways for coupled human–environment systems and strategies for finding solutions to sustainability problems could be identified (Wiek et al. 2012a).

– Transformational function (functional to the development of joint and coordinated strategies to solve sustainability problems): the transformational function was introduced at the beginning in early literature (Clark and Dickson 2003) and has also been discussed in later literature (Komiyama and Takeuchi 2006; van Kerkhoff and Lebel 2006). SS has been defined as a transformational agenda according to which 'the research community needs to complement its historic role in identifying problems of sustainability with a greater willingness to join up with the development and other communities to work on practical solutions to those problems' (Clark and Dickson 2003, p. 8059). In the transformational mode, scientists need not only acquire broader information on coupled human–environment systems and the causality links within sustainability problems, but they need to engage in arena with stakeholders having legitimate interest in the sustainability problems addressed and to develop joint and coordinated strategies for appropriate solutions. Therefore, as a consequence of its transformational mode, SS promotes social learning and mutual feedback (learning through doing and doing through learning) leading to co-production of knowledge with other stakeholder groups, such as businesses, politicians and society in a common process of problem identification and resolution (see for example the analysis of the collaboration networks' structure and evolution performed by Bettencourt and Kaur 2011). The current debate is on how far the SS endeavour has fulfilled the claim and promises of its transformational function (Wiek et al. 2012a,b).

Ten years after their emergence, the core questions have been revisited (Levin and Clark 2010; Kates 2011) in combination with research themes, as domains of investigation of SS, in a new set of key questions addressing the challenge of evaluating and implementing the knowledge produced in order to meet the great environmental and developmental challenges of this century.

2.2 Ontology of sustainability science

In information science theory, ontology is a 'formal, explicit specification of a shared conceptualisation' (Gruber 1993). Ontology of SS is defined as the set of concepts and the relationships within the domain of investigation, entailing the causality links between the drivers of the sustainability problems, as thoroughly discussed in Kumazawa et al. (2009). Globally recognised sustainability problems and objectives are reported in a plethora of strategic documents, covering almost every aspects of nature–humankind interaction. Widely cited examples of these documents are as follows:

– Agenda 21: 40 chapters defining the relevant issues and topics for sustainability from environmental protection (e.g. air pollution prevention, biodiversity, waste management) to role of stakeholders (both at economic and societal level) (UN 1992).
– International strategies for sustainable development [e.g. the EU sustainable development strategy (CEC 2001, 2009) that depict the EU vision on sustainable development, highlighting key topic to be mainstreamed within the EU policy context, such as climate change, sustainable production and consumption, sustainable mobility, health] or the recent UN report 'Resilient People, Resilient Planet: A future worth choosing' (UN 2012).
– Millennium development goals (UN 2000), which address main challenges for developing countries, such as biodiversity conservation, poverty and hunger and maternal health.
– OECD Development Assistance Committee Guidelines Strategies for Sustainable Development (OECD 2001), which addresses issues related to international cooperation focusing on issues such as poverty and hunger, political instability, population growth and marginalisation.

To address challenges posed by SD problems, in the context of scientific debate on SS ontology (Kumazawa et al. 2009), different aspects have to be analysed: (1) the SS domain of investigation, (2) the definition of 'what has to be sustained' and (3) the conceptualisation of different capitals to be assessed.

2.2.1 Domain of investigation

In terms of topics to be addressed, Komiyama and Takeuchi (2006) in their Editorial launching the international Journal 'Sustainability Science' define the domain of SS as the interconnection amongst three system levels global, social and human—which are all crucial to the co-existence of human beings and the environment, and to the promotion of a sustainable society. This implies a domain that covers broad and variegates topics and the need of interaction amongst different disciplines. Confirming the wide coverage of current SS landscape, Kajikawa et al. (2007) identify 15 research clusters (ranked by number of relevant publications) dealing with the 'sustainable' and 'sustainability' research domain: Agriculture, Fisheries, Ecological Economics, Forestry (agroforestry), Forestry (tropical rain forest), Business, Tourism, Water, Forestry (biodiversity), Urban Planning, Rural Sociology, Energy, Health, Soil, and Wildlife.

As far as the involvement of different disciplines is concerned, the role of collaborative networks across different geographical location and contributing disciplines is recognised as a fundamental step towards the consolidation of a unifying discipline and research community (Bettencourt and Kaur 2011). In particular, in the context of engineering (disciplines and approach), the blooming of different disciplines and perspectives contributing to SS development has been pointed out by Hasna (2010) through an extensive analysis of the SD domain.

2.2.2 What has to be sustained

Notwithstanding increasing efforts towards collaborative research, the ontological challenge for defining the SS domain relate to 'what should be sustained' is still open.

As presented in Section 1, numerous different definitions and interpretation of SD exist, but if we look at the common denominator, it is possible to identify four common questions (NRC 1999), which are still relevant:

1. What is to be sustained?
2. What is to be developed?
3. What is the relation between what is to be sustained and what is to be developed?
4. Over what scales in space and time are those relationships meant to hold?

Figure 1 illustrates how fundamental differences in values, goals and level of scale, underlying the above questions can lead to the 'sustainable development dilemma'. The figure structures the variety of ways the aforementioned questions can be answered, presenting different goals and values, the trade-off amongst them, the temporal and spatial scale. This classification reflects different perceptions and interpretation of SD.

An example within the 'What's to be sustained?' question is whether healthy ecosystems are viewed as a goal in themselves (e.g. biodiversity conservation per se even if not directly linked with human appropriation of goods and services), or merely as a mean to secure key ecosystems services for humanity (with a fully anthropogenic perspective).

Regarding the 'level of scale', the different perceptions on what is sustainable or not may be affected by the boundaries of the assessment. A solution perceived as sustainable at the national level may not be sustainable at the international one, e.g. the perceptions and realities of resource distribution between countries of the Northern and Southern hemispheres of the world diverge meaningfully.

Regarding 'What is to be developed?', socio-economic goals of development are strongly affected by specific perception and interpretation of SD.

The significance of the concept lays in the interrelation amongst the three SD pillars that conflict in practice. The underlying principles are also essentially different as well as the interpretations of what is to be sustained.

Even if both nature and life support and communities should be sustained, some consider that sustainability applies to the natural resource base itself, while others focus on the well-being of people and their livelihoods deriving from the resource base. These differences reflect biases of scientific disciplines as well as ideological differences that are usually adopted for defining weighting schemes in the evaluation of sustainability.

2.2.3 Conceptualisation of capitals

Historically, the values associated to each sustainability pillar were evaluated as capitals: natural,[3] social and economic ones. In recent years, the categorisation of capitals has been extended, e.g. as the four capital model of Ekins 1992 and in the five capitals framework (natural, human, social, manufactured and financial) developed by Porritt (2007) in which the capitals are not purely of instrumental value but represent an appropriate framework within which particular endpoints of intrinsic value can be identified.

One of the main consequences of having different perspectives on sustainability is the difference in the definition and the assessment of different capitals. The differences led to two basic approaches: strong and weak sustainability. Strong sustainability is based on the condition that natural capital provides functions that are not substitutable by man-made capital: each capital needs to be preserved for future generations. Weak sustainability reflects a view whereby natural and man-made capitals together comprise total capital. Natural capital is considered to be substitutable for man-made capital and weak sustainability occurs whereby the level of total capital passed onto future generations does not decrease (the inference being that man-made capital has replaced natural capital to maintain total capital) (Pearce et al. 1994).

Besides the discussion on weak and strong sustainability, we identified another level of complexity when addressing different capitals and associated values: the level of recognition of the capitals' value (Fig. 2). Natural, human and financial capitals are mainly based on objective and scientifically/globally recognised underpinning features, whereas social and manufactured capitals are subject to more local/regional/cultural-driven approaches to the evaluation (such as the concept of well-being, if we compare the perception of developed and

[3] Natural capital is the extension of the economic notion of capital (manufactured means of production) to goods and services relating to the natural environment (e.g. the stock of natural ecosystems that yields a flow of valuable ecosystem goods or services into the future). In the sustainability assessment of a system, the environmental pillar could be evaluated through the system capability to maintain the natural capital over time both quantitatively and qualitatively.

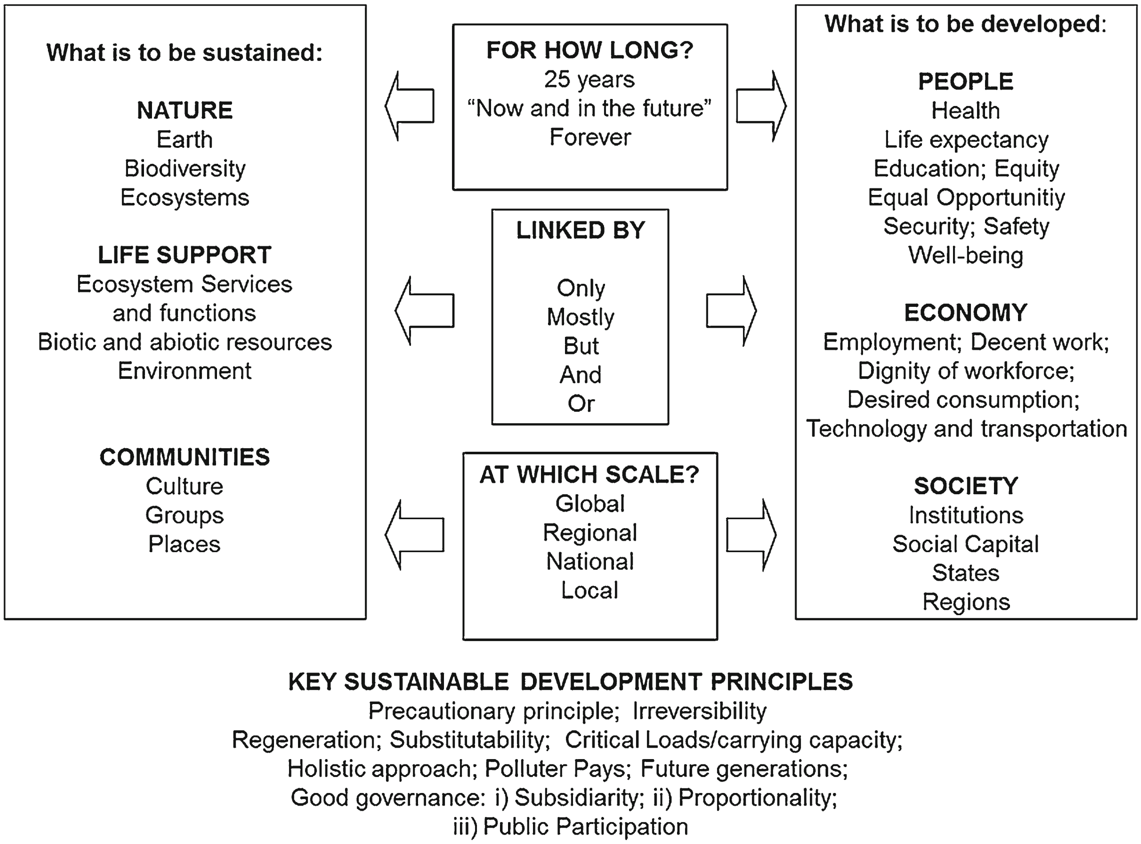

Fig. 1 Classification of the many framings of sustainable development, in which the key questions 'what is to be sustained' and 'what is to be developed' need to be considered in a multi geographical and temporal scale and need to be answered in light of key sustainable development principles (modified from NRC 1999)

developing countries, with different context and culture). This leads not only to ontological but also to methodological challenges in capitals evaluation.

Furthermore, some cross-cutting issues need to be considered in the evaluation of capitals, in order to address sustainability in a comprehensive way.

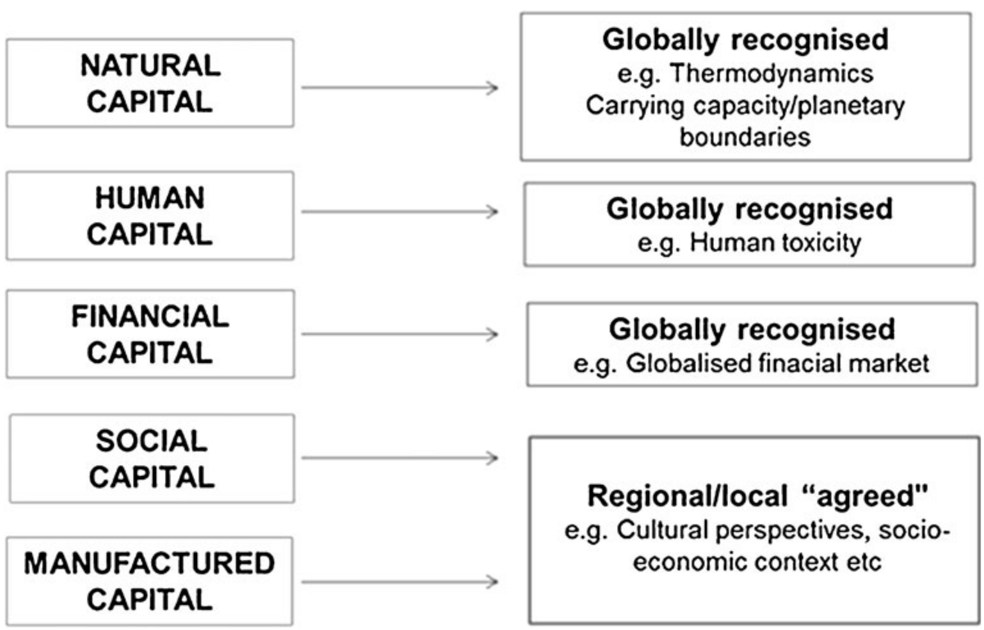

Fig. 2 Complexity in the evaluation of capitals. Natural, human and financial capitals could be based on objective and scientifically/globally recognised underpinning features whereas social and manufactured capitals are subject to more local/regional/cultural-driven approaches to the evaluation

Addressing limit of the resources and carrying capacity of the earth system In a recent paper of Rockström et al. (2009), availability of evidence-based thresholds for a safe operating space for humanity was discussed, charting research needs for identifying planetary boundaries. The boundaries are related with the evaluation of the Earth's carrying capacity (namely, number of individuals who can be supported or quantity of resources, which could be used in a given area within the natural resource limits, and without degrading the natural social, cultural and economic environment for present and future generations), including multi-scale spatial and temporal dynamics. For example, some impacts on biodiversity and ecosystem change are local; others are national, regional, or global. Some are extremely fast; others occur on very long time scales (Perrings et al. 2011).

Assessing vulnerability Vulnerability is defined as the degree to which a system, subsystem or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor (White 1974; Cutter 2001) The concept may be applied to environmental as well as to economic and social contexts (De Lange et al. 2010). Vulnerability presents formulations of vulnerability to environmental change as a characteristic of social–ecological systems linked to resilience (Adger 2006). According to Turner et al. (2003), the vulnerability analysis framework integrated in SA proves useful in directing attention to the interacting parts of the coupled system and helps to identify relevant gaps in information and understanding to reduce vulnerability in the systems as a whole.

Assessing resilience and adaptation The concept and measurement of resilience as developed in ecology was inspired by dynamic systems theory and catastrophe theory. The resilience is the capability of a system to recover after a certain stress. Its use in other disciplines and application to multidimensional systems is increasing, particularly with respect to sustainable systems management (Mayer 2008). Considering vulnerability and resilience in SA implies also accounting for indirect and cumulative effects that in some cases may be more critical than the direct ones. The relevance of the concept was recently stressed also in the context of the already mentioned key document of the United Nations 'Resilient People, Resilient Planet: A future worth choosing' (UN 2012).

2.3 Epistemology of sustainability science

Epistemology is the discipline of verification and logical confirmation of the explanatory structure of scientific theories, and its primary objective is to guarantee the undoubted safety of scientific methods and knowledge (Lenk 1988). Epistemology's function is to examine and evaluate the construction and foundations of scientific practices as well as to search for alternatives in order to provide solutions to scientific challenges.

The increasing concern about the reconciliation between the current economic system based on the paradigm of constant economic growth and society's development goals as well as the environmental limits of the earth posed relevant challenges to the scientific community and pushed it to find new models and paradigms. The paradigm shift from mode I—academic, mono-disciplinary, technocratic, certain and predictive—to mode II science—academic and social, trans- and inter-disciplinary, participative, uncertain and exploratory (Funtowicz and Ravetz 1993; Gibbons et al. 1994; Martens 2006)—from basic or applied to 'use-inspired science'—where research trajectories are defined by the problems to be solved, context-embedded, having a linking knowledge to action function (Stokes 1997; Clark and Dickson 2003; Clark 2007) —entails a new type of knowledge and knowledge production.

This new type of knowledge must be capable to address and understand the complex, multi-dimensional human–nature interaction, the 'social–ecological systems' dynamics, and must be immediately useful for policy and management for providing solutions to real-world, life-threatening, having long-term impacts, highly complex–systemic problems that cannot be solved with simple remedies (Funtowicz and Ravetz 1993).

It must be produced through collaboration amongst different disciplines and different stakeholders, including multiple societal worldviews, balancing and negotiating amongst different interests, in an iterative circular co-production process, linking scientific and experiential knowledge, enabling mutual learning amongst researchers from different disciplines as well as from actors outside academia, promoting societal learning and solutions that are legitimate, negotiated and accepted by the social, economic and political context (Martens 2006; van Kerkhoff and Lebel 2006; Walter et al. 2007; Talwar et al. 2011; Lang et al. 2012).

The knowledge for action implies the validity of multiple epistemologies and the emphasis on action and social learning compared to the abstract cognitive theorising of traditional scientific approach. In SS, through adaptive management, policies become hypotheses and management actions become the experiments to test these hypotheses (Burns and Weave 2006).

SS does not aim to define a single and unique truth but to gain comprehensive and robust knowledge capable of addressing and solving complex and societally relevant problems, taking into consideration the whole range of values, perspectives and interests from all actors that have a legitimate interest in the problem solution.

Osorio et al. (2009) reviewed several epistemological theories for SS: transactional (Buckley 1972), reflexive (Brunet Icart and Morell Blanch 2001) and political (as the post-

normal science of Funtowicz and Ravetz 1993) epistemology. Analysing the suitability of the above-mentioned epistemologies, the authors proposed a framework, modified from Gallopin (2001), in which:

- The study object is the socio-ecological system, possessing a wide range of dimensions (from global to local) and integrated by two subsystem (human and ecological).
- The approach is essentially inter-disciplinary, accounting for both quantitatively and qualitatively dimensions. The discipline requires the identification and comprehension of the system components and the relations established amongst them. A deep understanding of the system's dynamics is also essential, analysing how the system's components and interactions generate processes, how responses are generated by the system; which are the emergent properties and transformation/adaptation inside the system.
- The truth criterion has to be reassessed because the existence of facts and phenomena that are not comprehensible by means of the positivist model cannot be further denied.

Current elaborations about epistemological issues within the SS community aim to investigate how and what knowledge is being generated in SS and whether knowledge produced is capable of understanding the complex human–nature interaction (enhanced understanding) in an integrated way and comply with the transformation mode of sustainability research (Wiek et al. 2012a).

2.4 Conceptual framework for sustainability science

Several conceptual frameworks have been proposed to present the main features of SD and SS. A review of these conceptual frameworks is presented in Kajikawa 2008. In the literature, there is a clear need for systematisation of knowledge in terms of concepts and related nomenclature for SA and SS, as almost each paper adopts its own terminology, in many cases without providing a definition. Therefore, in order to address this need and to provide a synthesis on our perspective on SS, as reported hereafter, we charted a conceptual framework (Fig. 3) to present SS peculiarities and to systematise the knowledge area. Additionally, we defined the related terminology (Fig. 4) adopted in this paper highlighting the hierarchical differences associated with each term.

Regarding the conceptual framework for SS, contrary to other disciplines, it requires the evolution of two paradigms (Sala and Castellani 2010): not only the scientific[4] one (Kuhn 1970), towards more integrated and inclusive approaches to

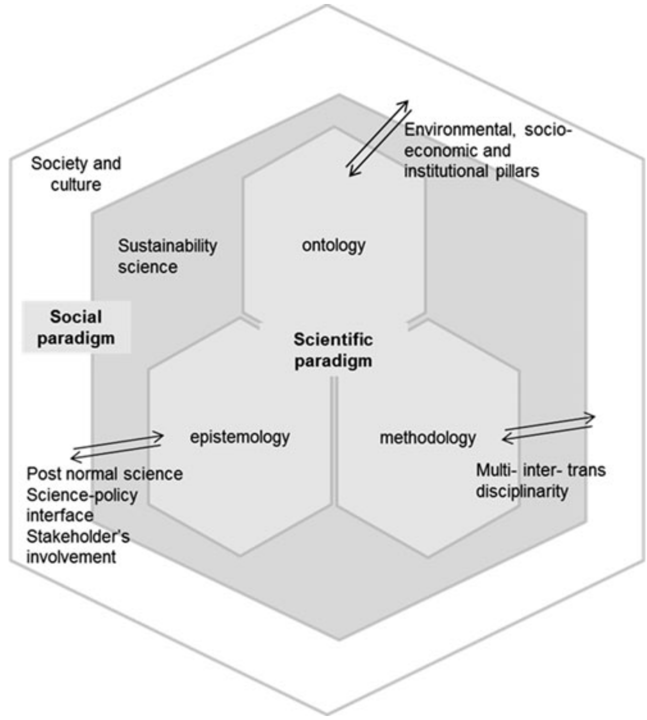

Fig. 3 Conceptual framework for sustainability science as interface between scientific and social paradigm for handling sustainable development challenges characterised by complex relationship between nature and humankind are. The scheme has to be considered on a multi temporal and spatial scales

problem solving but also the social[5] one (Capra 1996), towards new cultural and natural–humankind interactions. Hence, in the conceptual framework, SS acts as a bridge between the two paradigms as the social paradigm is the cradle of values and perspectives on sustainability and the scientific paradigm structures problem definitions and solutions. First of all, the SS domain is embedded in the wider domain of society and culture, including the political context, which underpins and informs the social paradigms. Secondly, SS builds on scientific paradigm, which defines the scientific core of the discipline, characterised by its own ontology, epistemology and methodology (Kuhn 1970). Based on the discussion performed in the previous sections, and following the structure of the proposed framework, we defined SS as:

> 'solution-oriented discipline that studies the complex relationship between nature and humankind, conciliating the scientific and social reference paradigms which are mutually influenced- and covering multi temporal and spatial scales. The discipline implies a holistic approach, able to capitalize and integrate sectorial knowledge as well as a variety of epistemic and normative stances and methodologies towards solutions' definition'.

[4] The scientific paradigm is the set of concepts, values, techniques, shared by a scientific community in order to define problems and solutions (coherent with the scientific discipline).

[5] The social paradigm is the set of concepts, values, perceptions and behaviors, shared by a community, leading to a vision of reality. This vision informs the way the society is organized.

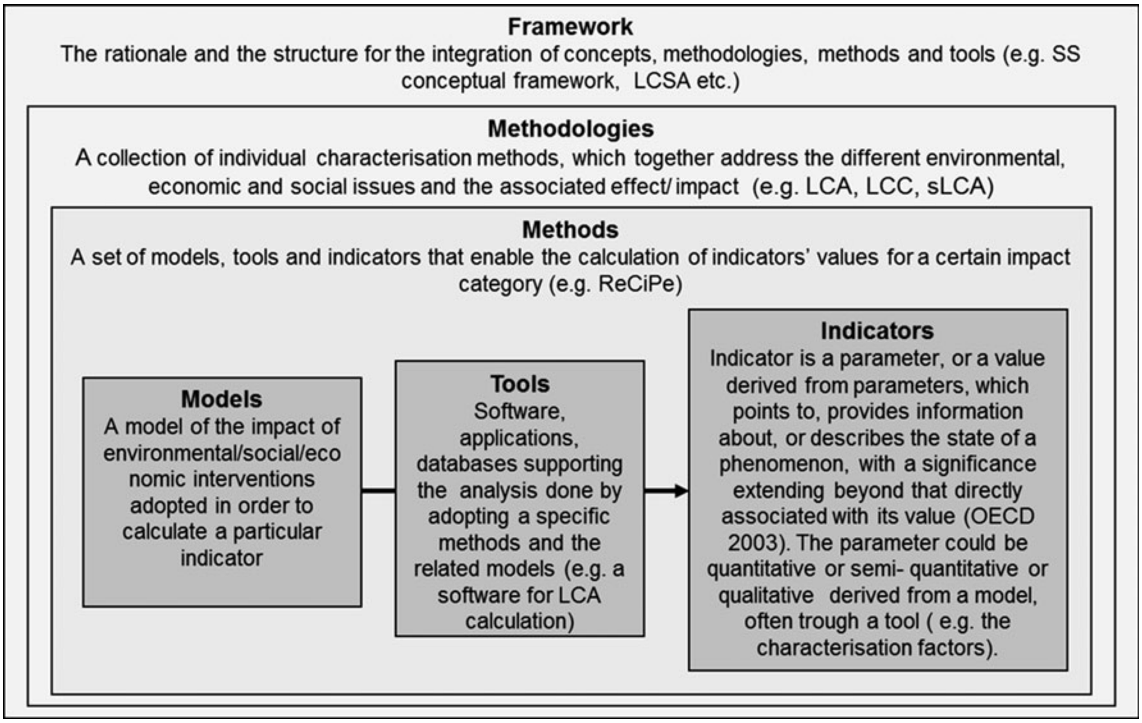

Fig. 4 Terminology adopted in this paper. The terms are reported highlighting the hierarchical relationship between them. The framework definition is the key level for setting the rationale and the structure for the further integration of single methodologies, methods, models, tools and indicators

This definition implies that ontological, epistemological and methodological aspects of the discipline are interlinked.

At the ontological level, the SS domain relates with different pillars (the environmental, economic and social–political–institutional ones) and the scientific and social paradigms imply a set of values, concepts, guiding principles (e.g. precautionary principle, dematerialisation, decoupling) as well as perspectives (e.g. LCT) used to define, assess and solve problems. Figure 1 represents on overview of the ontology part of the SS framework.

At the epistemological level, SS builds on the so-called 'post-normal' science, in which society involvement, science–policy interface and active involvement of stakeholders are essential. SS is indeed subjected to a number of different conceptual interpretations that depend on the social–political contexts and on the scientific dimension from which the factual phenomena are observed and analysed (Rios et al. 2005; Patterson 2010). This implies that any SA coherent with the framework described above has to deal with the two reference paradigms, scientific and social. Furthermore, the SS paradigm aims to encompass different magnitudes of scales (of time, space, and function), multiple balances (dynamics), multiple actors (interests) and multiple failures (systemic faults) (Martens 2006).

The methodological level is, therefore, influenced by the ontology and the epistemology of SS and should be characterised by multi-inter-trans-disciplinarity in addressing, assessing and providing solutions to problems. Although trans-disciplinarity is considered the most appropriate approach to SS, existing methodologies and related methods, models, tools and indicators are more appropriate to handle multi- or inter-disciplinary aspects (adopting for each level specific and hierarchically different perspectives). So far, few attempts to address principles of trans-disciplinary sustainability research have been experienced in empirical studies (see e.g. Lang et al. 2012; Wiek 2007). Furthermore, the methodological level implies also coherence with the reductionist or holistic approach, set at framework level. A detailed discussion on methodological issues is presented in Section 3.

Furthermore, credibility and success of SS in actually promoting sustainable transitions, depends not only on robust epistemological and methodological foundations (scientific adequacy of the technical evidence and arguments) but also on other cross-cutting quality criteria, such as salience (practical relevance of research results and assessment to the needs of stakeholders and policy makers) and legitimacy (in term of respect, fair treatment and balance of different interests, values and beliefs of stakeholders, transparent process and unbiased in its conduct). In fact, sustainability problems are real-world problems and stakeholders have a legitimate interest in being involved in their solution (Cash et al. 2003; Clark and Dickson 2003; Wiek et al. 2012a).

3 Sustainability assessment methodologies and methods: how to evaluate progress towards sustainability

SS, intended as a solution-oriented field of research, ought to link science with actions. Therefore, the discipline focus is not basic research but the integration, capitalisation and co-production of knowledge coming from different disciplines and actors towards the analysis of options and the definition of win–win, shared and participated solutions.

This process of integration and co-production of knowledge requires specific methodologies, methods, models, tools and indicators. Indeed, all these are hierarchically different, as presented in Fig. 4, and represent crucial elements of the methodology's area presented in Fig. 3, strongly linked with ontological and epistemological foundation of SS. To address sustainability problems, a plethora of methodologies, methods, models, tools and indicators for SA have been developed over the past 30 years. No single methodology and method but several in continuous evolution can offer support in acquiring a better insight into complex problems of sustainability and attempt to respond to the new paradigm in accordance with the ontology and epistemology described in the sections above. We continue moving towards an 'indicator zoo' characterised by a multitude of approaches, allegedly comprehensive in addressing sustainability, but still with only limited impact on policy and outcomes that are priorities for sustainable development (Pintér et al. 2005).

Amongst the wide spectra of methodologies needed in the context of SS (from scenario development to problem identification, assessment, solving, etc.), we concentrate here on those focused on SA. Terms such as Integrated Assessment and Sustainability Assessment[6] are used to label 'new' approaches to impact assessment that are designed to direct planning and decision making towards SD (Hacking and Guthrie 2008).

SA can contribute to bridge the knowledge to action gap providing efficient and reliable methodologies to measure progress towards sustainability and to assess SD objectives and goals. Although SD is not a destination, but a dynamic process of adaptation, learning and action, objectives and goals towards a more balanced integration between nature and humankind have to be agreed upon and set both at societal and policy level.

SS methodologies and methods need to be coherent with the underpinning ontology and epistemology, following scientific paradigm shifts [corresponding to the shift from mode 1 to mode 2 science (Gibbons et al. 1994)]. Therefore, according to SS literature, several methodological requirements can be outlined:

- Analytical–descriptive. The methodologies and related methods must be appropriate in addressing: the key features of sustainability problems, the current state (for example a systemic analysis method is needed for addressing the systemic nature of the problem, allowing for a comprehensive current state analysis considering all driving forces); the potential systemic changes, consequences, feedbacks and lock-in and lock-outs of a particular development in specific areas (Martens 2006; Wiek at al 2012a).
- Solution-oriented. The methodologies and related methods have to: develop goal-oriented and actionable knowledge, that is sufficient for solving the problem at hand, and realise sustainable transition towards desirable state and goals (e.g. a SA method is needed to provide direction for the solution strategy, support the decision-making process and social learning) (Schultz et al. 2008; Jerneck et al. 2011); support transition management approach developing visionary, evolutionary learning process (Rotmans et al. 2001; Kemp and Rotmans 2004); to assist the decision making in assessing sustainability at systemic level, making concrete both problems and solutions; moving from predictive to exploratory analysis.
- Participative. The methodologies and related methods have: to be designed and developed in a participatory, interactive (non-extractive) collaborative way; to be shifted from supply- to demand-driven; to facilitate knowledge co-generation through participation processes of scientists and stakeholders interacting from problem framing to strategy implementation, transparently balancing inputs and facilitating knowledge claims, shared control over the process and accountability of results (Scholz 2011; Talwar et al. 2011; Kasemir et al. 2003; Wiek et al. 2012a); to increase trust, ownership and empowerment; to manage contested values by different stakeholders, different power dynamics and the urgency of decision making (Funtowicz and Ravetz 1993).
- Suitable for scalability, transferability and comparability. The methodologies and related methods have to allow for scaling-up and transferability of the solution options generated, ensuring comparison of alternative solution options and providing synthesis thereby strengthening the capability of solving sustainability problems (Wiek et al. 2012a).
- Capable to manage uncertainties of information, especially in broad trans-disciplinary systems in which complexity may dramatically increase. An example could be the analysis of the impact associated with biofuels, in which a number of direct and indirect environmental,

[6] Other synonyms adopted: Triple Bottom Line assessment, 3E Impact Assessment (Environmental, Economic, Equity), Extended Impact Assessment, Sustainability appraisal.

economic and social consequences are expected and are mutually affected (e.g. deforestation for biofuel production, competition of land for energy and food purpose, market reaction to increasing commodity costs).

In order to analyse the capability of existing SA methodologies and related method to adequately support the analysis and the solution related to sustainability, several comparative studies have been published.

Various reviews have categorised methodologies, methods, models and indicators developed for describing sustainability and assisting the decision making (e.g. Todorov and Marinova 2011; Boulanger and Bréchet 2005). They include analytic methods, participative methods, pictorial visualisation, conceptual models, sophisticated models coupled with the current advances in information technology and more managerial methods (as the transition management approach developing visionary, evolutionary learning process) (Rotmans et al. 2001; Kemp and Rotmans 2004). In the following section, a meta-review of selected comparative studies on SA is presented.

3.1 Meta-review on sustainability assessment methods

We performed a meta-review of comparative studies on SA aiming at exploring the features and criteria used for identifying peculiarity of SA, comparing LCA amongst other SA methodologies and methods and highlighting how current SS literature evaluates SA.

The meta-review covers publications in peer reviewed journals in the last 7 years in order to take into account recent developments and critical analysis thereof. Papers were retrieved trough search engines such as Science Direct and Scopus, using the following keyword logical expression: (‘life cycle assessment’ AND ‘sustainability assessment methodologies’ OR ‘methods’ OR ‘tools’ OR ‘indicators’). Each comparative study was based on several features and criteria, driven by the specific objective of the comparison (e.g. suitability for policy decision making, capability of spatialisation, etc.). Amongst the numerous papers reviewing SA methodologies and methods,[7] we selected those complying with the following criteria:

- Assessing life cycle thinking/assessment against other SA methodologies and methods
- Comparing and contrasting existing SA methodologies and methods in order to highlight critical areas and providing suggestions for further development
- Defining SA peculiar features
- Focusing on methods’ suitability in being applied for SA
- Listing recommendations for improving the SD directedness of assessments

In Table 1, the papers selected for the meta-analysis of the SA methodologies and methods are reported. As each paper has a unique set of evaluation criteria, we reported the key sustainability criteria used for assessing the methodologies and methods by the reviewing authors.

It is worth noting that having searched for LCA as a keyword for the meta-review, almost all the papers belong to the environmental science domain. This implies that reviews on methodologies, methods and models frequently used in socio-economic policy making were not included, (e.g. Boulanger and Bréchet 2005, analysing macro-econometric models, computable general equilibrium model, optimisation models, model system dynamic model, multi-agent simulation model, Bayesian network). Furthermore, within the reviewed papers, the methodologies and methods assessed and compared with LCA are sometime hierarchically different. In some papers, procedural methodologies, such as environmental impact assessment (EIA), are compared with analytical methods such as material flow analysis (MFA). It is relevant to point out that LCA could be used as an analytical methodology supporting several assessment procedures (such as SEA, EIA, etc.), but this aspect goes beyond the scope of the present study.

Starting from the results of the meta-review, we identified specific features of SD-oriented methods aiming, firstly, at highlighting ontological, epistemological and methodological key issues towards robust methods for SA. Secondly, capitalising on the findings of each review’s paper, and considering the broader discussion on SS of the Section 2, for each issue, a recommendation for a robust sustainability assessment method is given. Finally, we reported for each issue, how life cycle-based methods were evaluated against each specific SD feature.

In the following sections, the specific features of SD-oriented methods are reported.

3.1.1 Value choices underpinning methods’ development and adoption

The choice of methods for sustainability assessment may entail various ethical and practical consequences. The effectiveness of SA is often highly questioned because of the value-based nature of the assumed goal (sustainable development) because effectiveness itself can be determined through different theoretical framings without a specific guarantee of sustainable outcomes (Bond et al. 2011). In most cases, the choice of the evaluation tool is made by the analyst(s) without taking into consideration the values of the

[7] Across the reviewed papers on SA, the terminology is often used not consistently, adopting “methods” (Thabrew et al. 2009; Patterson 2010; Jeswani et al. 2010), “tools” (Ness et al. 2007; Finnveden and Moberg 2005; Kissinger and Rees 2010), “approaches” (Gasparatos et al. 2008; Hacking and Guthrie 2008), “indices” (Mayer 2008) and “methodologies” (Singh et al. 2009) to indicate the same object.

Table 1 Meta-review of sustainability assessment: analysed methodologies, methods, models, indices and indicators and the criteria used for the assessment are reported for each paper

Review's reference	Analysed methodology /method/model/indices/indicators	Key criteria used for the assessment within each reviewed paper
Finnveden and Moberg 2005	Environmental impact assessment (EIA), System of economic and environmental accounting (SEEA), LCA, Material flow analysis (MFA), Input–output analysis (IOA), Environmental management system (EMS), Risk assessment (RA), Ecological footprint (EF)	Differentiation between analytical and procedural tools for business and policy decision making
		Kinds of impact covered (use of resources, environmental impact and/or economic aspects)
		Object of the evaluation
		Distinction between accounting vs. change-oriented methods
Gasparatos et al 2008	Emergy, exergy (EF), Contingent valuation method (CVM), Cost–benefit analysis (CBA), Index of sustainable economic welfare (ISEW), composite indicators	Focus on methods able to capture the quantitative measure of shift towards sustainability, following a reductionist perspective. Monetary tools, biophysical models, sustainability indicators/composite indices developed in economics, statistics, ecology, engineering and town planning
		Criteria for holism assessed: consider economic, environmental and social issues; predict future conditions under different scenarios; compare the likely outcomes of different action; communicate the results in an appropriate form to the stakeholders
Ness et al 2007	Over 20: LCA, EIA, SEA, Human development index (HDI), regional flows indicators (MFA/SFA), ISEW, Genuine progress indicator (GPI), EF, Wellbeing index (WI)	Capability of methods (indicators/indices; product-related assessment; integrated assessment) to integrate nature-society systems, to address local to global dimension and short-term/ long-term perspectives; to act retrospectively or prospectively
Hacking and Guthrie 2008	EIA, SEA, Social impact assessment (SIA), LCA, MCA, CBA, RA, Health impact assessment (HIA)	Methodologies and methods assessed considering if SD 'themes' are covered ('comprehensiveness'); the assessment techniques that are used and/or the themes that are covered are aligned/ connected/ compared/combined ('integratedness'); the focus/ perspective is broad and forward-looking ('strategicness')
Mayer 2008	12 indices, amongst others: WI, environmental sustainability index, fisher information index, ISEW, genuine saving index, sustainable national income, emergy, EF	System boundaries, data inclusion, normalisation and weighting, aggregation methods (bottom–up: sums, averages, and ratios vs. Bottom–up: principal component analysis, regression, and information theory vs. top–down: carrying capacity/accounting)
Thabrew et al 2009	SB-LCA; LCA, EIA, RA	Capability of methods to allow multi-stakeholder interactions
Singh et al 2009	Over 40 methods/tools/indicators/indices, amongst others LCA, EF, WI, HDI	Sustainability methods /indicators applied in policy practice considering:
		sustainability indices domain (what the indicator measure), methodological issues [formulation strategy, techniques/ methods employed for construction of index like quantitative/qualitative, subjective/objective, cardinal/ ordinal, unidimensional/multi-dimensional; normalisation, weighting and aggregation methodology; measure of sustainability in terms of input ('means') or output ('ends')] scaling [measure (a) across space ('cross-section') or time ('time-series') and (b) in an absolute or relative manner]. Data availability across time and space. Flexibility in the indicator for allowing change, purpose, method and comparative application. Clarity and simplicity in its content, purpose, method, comparative application and focus
Kissinger and Rees 2010	Regionalised approaches: (MFA), (LCA), environmental input–output analysis (EIOA) and (EF)	Relevance of spatially differentiated approach. Methods analysed considering interregional approach and illustrating some existing and emerging methods for quantifying, analyzing and modelling interregional linkages
Jeswani et al 2010	LCA, EIA, SEA, Multi-criteria decision analysis (MCDA), (MFA), Substance flow analysis (SFA), (CBA), Energy, exergy analysis (EA), (EIOA) and extended EIOA/hybrid analysis, Risk assessment (RA), Life cycle costing (LCC), Eco-efficiency analysis (EE), Social life cycle assessment (sLCA)	Analytical vs. procedural tools, focus on levels/scales (plan, project, product, policies), coverage of SD dimensions, capability of dealing with cross-pillar issues
Patterson 2010	LCA, EIOA, CF, EF, Emergy, ecological pricing and others	Analysis on the basis of purpose, standardisation level, capability of addressing indirect inputs and effects and system-wide impacts vs. on-site narrower impacts, methodological rigor vs. resonance (public perception)

affected stakeholders. By choosing the analytical method the analyst essentially 'subscribes to' and ultimately 'enforces' a particular world view as the legitimate yardstick to evaluate the sustainability of a particular project (Gasparatos 2010). No method could avoid being the result of a certain scientific, cultural and political background. Notwithstanding the necessity of the most objective assessment, a transparent presentation of values behind the assessment is crucial for ensuring credibility and robustness to the sustainability assessment methods (e.g. strong or weak sustainability, clear definition of the guiding vision and perspective).

Life cycle-based methods entail values choices in different steps, notably in the choice of the impact assessment methods and the weighting step, in which different perspectives (e.g. egalitarian) are possible.

3.1.2 Completeness of scope

Completeness of scope is related to the capability of covering all the relevant and interdependent issues for sustainability. Clearly, different perspectives on sustainability may imply different needs in term of completeness of scope, e.g. according to the four main interpretations of the concept of sustainability mentioned in the introduction: ecological, economic, thermodynamic and ecological–economics, public policy and planning theory. Therefore, the completeness of scope of an SA method may be evaluated considering its capability of covering the issues presented in the strategic documents mentioned in the ontological section of SS (e.g. Agenda 21) and integrating key principles (e.g. encompassing system wide analysis; assessing all dimensions of sustainability, dealing with non linearities and dynamic features) and concepts related to sustainability, such as carrying capacity, vulnerability and resilience and indirect effect, to mention just a few.

Life cycle-based methods struggle to be comprehensive in terms of coverage of potential impacts associated to an intervention (e.g. the number of impact categories covered by the life cycle impact assessment phase), but concept such as the carrying capacity, vulnerability and resilience are still neither mentioned nor modelled.

3.1.3 Integrated assessment

Integrated assessment is sometimes merely used to refer to extending the coverage of assessment rather than to 'combining the parts'. According to Lee (2002), the term may be used in at least three general senses, namely, bringing together different types or categories of impacts, e.g. biophysical and socio-economic (horizontal integration); linking together separate assessments undertaken at different levels (vertical integration); and integration of assessments into decision making. Amongst methods, accounting for cause–effect relationships and interdependency amongst pillars is not fully developed. Furthermore, as reductionism is still the dominant paradigm for SA (Gasparatos et al. 2008), system-wide and holistic approaches are still lacking. An SA method should be based on integrated assessment, dealing with cross-sectorial issues (vs. a single-sector focus), highlighting cross-sectorial interlinkages, and applying horizontal and vertical integration.

Life cycle-based methods are considered suitable for integrated assessment but are still lacking in the cross cutting assessment (interdependency amongst categories of impacts/ interdependency amongst pillars). There is a need to move from multi-disciplinary to inter- and trans-disciplinary integrations.

3.1.4 Strategic and solution oriented

Based on the proposal of (Noble 2000) and integrated with the results of the meta-review, an SA methods assessment should fulfil the following criteria to be considered strategic: (1) address the wider context considering a holistic view, upstream and downstream consequences (vs. analysis limited to a few obvious phases); (2) operate on the level of vision statements, objectives and measures; (3) be proactive; (4) take alternatives into account; (5) define clearly the decision context in term of actors involved, scale, complexity, activity and impact of interest; (6) assess alternative scenarios (vs. status quo assessment); (7) support scenario development; and (8) promote consensus building for joint projects.

A common theme in descriptions of SD-directed assessment is that the assessment goal should be shifted from avoiding negative impacts, to also proactively enhancing positive impacts, and then to do this in a manner that contributes to SD (Hacking and Guthrie 2008). For example, promoting not only the reduction of environmental impact in the traditional approaches of cleaner production but mainstreaming the concept of circular economy, rooted in industrial ecology, which envisions a form of material symbiosis between otherwise very different companies and production processes (Andersen 2007).

Life cycle-based methods are able to cover (1), (4), (5) and (6) but less efficient in covering (2), (3), (7) and (8). Being proactive is crucial for contributing not only to the evaluation of sustainability performance of products but also for promoting SD-oriented innovation, e.g. ecoinnovation. This goal could be reached integrating LCA with other solution-oriented approaches (e.g., as proposed by Castellani and Sala 2010, the integration of LCA with Lean Thinking as well as with Ecodesign principle and Theory of Inventive Problem Resolution—TRIZ, etc.) or integrating sustainability principles (e.g. the integration of 'green chemistry principles' presented by Tabone et al. 2010).

3.1.5 Multiscale (temporal and geographical)

The issue of the scale sustainability should model and assess, has been debated ever since that concept came under discussion. According to Kissinger et al. (2011), an approach to sustainability conscious of interregional connections reveals that: (1) virtually every significant human population or country lives, in part, on energy/material flows to and from distant places elsewhere around the world; (2) production, consumption and policy decisions in any given local context have the potential to create unforeseen unsustainable burdens on connected productive ecosystems in distant locales; (3) ecological change in one region has the potential to jeopardise the sustainability of other regions; and (4) society in almost any region has interests in sustaining the vitality of ecosystems in other regions.

Therefore, an optimal SA method should be multi-scale, i.e. able to deal with different and wide spatial and temporal scale (Hacking and Guthrie 2008; Jeswani et al. 2010), integrating global and local perspective, and provide insight into linkages between events on both the macro- and micro-scale, accounting for different time horizons, time preferences, discounting and consistency with key concepts of sustainability (inter-generational equality).

Recent developments of life cycle-based methods have started addressing the spatial (e.g. Potting and Hauschild 2006; Wegener Sleeswijk 2011) and/or the temporal (e.g. Levasseur et al. 2012) scale, but these developments are still perceived as preliminarily.

3.1.6 Applicability and comparability/ data availability

In order to bridge the gap between theory and practice, the applicability of SA methods is crucial. Three main concerns emerged from the meta-review: (1) the extent of applicability of the method; (2) the flexibility in terms of context of application (product, plan, project etc.), requiring, also, different procedural vs. analytical approaches; and (3) integrability amongst tools/data/information. The inherent nature of SA methods (especially in a transdiciplinary context) may imply reducing comparability due to a certain degree of subjective and qualitative assessment as well as, critical methodological issues such as: allocation or joint production problems; weighting; commensuration and boundary setting; incommensurability of values especially when dealing with non-algorithmic approach, which may be implemented by some forms of multi-criteria evaluation; or when dealing with capitals and labour (Martinez-Allier et al. 1998; Patterson 2010).

Therefore, an SA method has to be able to guarantee as far as possible applicability and comparability, being able to tackle with data scarcity or incommensurability.

LCA, being a standardised (by ISO) methodology, allows—in theory—for wide applicability and potential comparability. The fact that the ISO standard leaves a certain degree of freedom—in choosing system boundaries and methods for impact assessment—reduces the full comparability. To overcome this limitation, several international initiatives exist, which address the issue of LCA study comparability, e.g. the ILCD Handbook (EC-JRC 2010b) and the environmental footprint methodology (CEC 2012) under development.

A balance between flexibility of procedural approaches [being normative (e.g. SEA directive) or standardised (e.g. ISO 14040—LCA)] and rigor/comparability of analytical tools has to be identified.

3.1.7 Scientific robustness

As improving SD relevance implies great uncertainty, sustainability assessment needs to integrate uncertainty assessment approaches, methodologies and tools, in order to distinguish between true uncertainties and variability, explicitly assess uncertainties and gain knowledge of the source of uncertainties. Actually, there is an increasing demand for more and better quality in the evaluation (Gasparatos 2010), adopting principles such as impartiality, independence, credibility and usefulness (OECD 2007). Therefore, a robust SA method should entail a framework for dealing with variability and uncertainties, both at the level of their assessment and reporting. A proposal for integrating sensitivity analysis within sustainability assessment has been recently released (Ciuffo et al. 2012).

In the reviewed papers, life cycle-based methods are generally considered able to deal with uncertainty at the level of parameters, models and scenarios.

3.1.8 Participation of stakeholders

It has been widely recognised that collaborations and partnerships within and across different stakeholder groups are critical conditions for SS and its real-world impacts (Blackstock et al. 2007; Spangenberg 2011; Talwar et al. 2011; Wiek et al. 2012a; Lang et al. 2012). Actually, applying SS means developing research activities, which are aimed at problem solving and are solution oriented. Solutions are mainly based on co-responsabilisation of all the actors/stakeholders. This also requires: building collaborative research team using a 'common language', facilitating participation through capacity building and using boundaries organisation as an intermediary between research/assessment and implementation. Almost all the reviewed papers identify the involvement of stakeholders as a crucial issue in SA methods development and application, but rarely is a proposal put forward on how to actually involve them. Ideally, an SA method should be open and structured for allowing the participation of stakeholders along the whole assessment process (from problem framing, design of

methodology, goal and indicator setting, test of the methodology and application, to inclusion in the decision-making process).

Stakeholder participation is recognised as an important step, and it is required by the ISO standards (e.g. in the critical review panel). It is also a common practice for some tools (e.g. EPD and Ecolabel). However, life cycle-based methods are still in an early stage in the involvement of stakeholders within the assessment process and examples so far are mainly focused on involvement of actors within the supply chain (e.g. Nakano and Hirao 2011).

3.2 Key criteria for assessing and developing sustainability assessment methods

According to the discussion on the foundation of SS presented in Section 2, and the key features presented above, we identified a number of key criteria for developing and assessing SA methods and in particular life cycle-based methodologies. These criteria, reported in Table 2, are meant to assess progress of life cycle-based methodologies in the context of SS, and they are applied to assess existing frameworks of LCSA (as in the analysis reported in Sala et al. 2012).

Table 2 Key criteria for developing and against which assessing sustainability assessment methods, specifically aimed at evaluating LCSA

Value choices	Values are explicitly mentioned
Completeness of scope	All dimensions of sustainability are assessed (vs. one dimension of sustainability) and key topics addressed
	Encompass system wide analysis
	Limit of the resources and carrying capacity/ planetary boundaries of the earth system
	Vulnerability
	Resilience
	Indirect effects
	Deal with non-linearities and dynamic features
Geographical and temporal scale of the assessment	Multi-geographical and temporal scale may be handled
Strategicity	Clear definition of the decision context
	Assess alternative scenarios (vs. status quo assessment); support scenario development
	Consider a holistic view of the issues, including upstream and downstream consequences (vs. analysis limited to one or two obvious phases)
Methodology	Integratedness: deal with cross-sectorial issues (vs. a single-sector focus) and highlight cross-sectoral interlinkages
	Applicability/comparability
	Data scarcity
	Comparability
	Transparency
	Scientific robustness: dealing with variability and uncertainties
Participation of stakeholders	Capability of integrating different perspectives and of interacting with stakeholders

4 Discussion

Kates et al. (2001) core questions on SS still represent the main challenges for future research together with emerging issues regarding usability, implementation and transferability of enhanced understanding about complex coupled human–nature interaction and its re-integration into societal and scientific practice, quality of participation and evaluation of effectiveness of sustainability research processes and practices (Lang et al. 2012). The present study aimed at depicting current debate on SS as a basis for identifying the main challenges for a comprehensive and robust approach to SA and related methodologies and methods, highlighting: (1) the domain of SS (ontology), in other words what a SA methodology should assess; (2) the epistemological foundations of SS, and how these influence the scientific paradigm and the assessment methodologies; and (iii) the peculiarity of SA methods and how LCA is perceived in recent literature on SA. The analysis of the state of the art in SS and results of the meta-review on methodologies and methods show that there are still many open issues and further research needs to be dealt with in order to develop robust SA.

More specifically, at the level of ontology, the main challenges are related to the comprehensiveness of the science in addressing different capitals, values and goals and respective trade-offs, whereas, at the level of epistemology, the key point is knowledge innovation, in other words, how to move to the mode 2 science, through collaboration amongst different disciplines and a broader societal learning.

From a methodological point of view, in our opinion, single methodologies or methods are actually not able to answer the challenging questions posed by SS. The co-existence and integration of existing methods is paramount, but not enough. There is a need for hierarchically different methodologies and methods, capable of modelling different impacts on different capitals, building and evaluating scenarios, properly addressing uncertainties, managing different values and power dynamics and allowing for broader and more effective stakeholder involvement.

Capitalising on the recommendations coming from the meta-review, and considering the conceptual framework proposed by us and outlined in Section 2.4, crucial issues for further developing SA methodologies and methods are a holistic and system wide approach, a shift from multi- and inter- towards trans-disciplinarity; multi-scale (temporal and

geographical) perspectives; quality of stakeholder participation. Ideally, SA should fulfil these requirements as far as possible adopting suitable methodologies and the related methods, striving to clearly indicate which integration is needed for a comprehensive assessment.

In the reviewed papers, LCT and its basic principles are acknowledged as relevant for SA. Nevertheless, LCA is not considered as a reference framework in which other methods could also find a place. Moreover, it is also surprising that in an extensive literature review on sustainability and engineering, (such as the one by Hasna 2010) life cycle thinking and assessment are not even mentioned. This aspect has to be further investigated, in order to understand whether it is due to a lack of exchange between the two communities of SS and LCT or to the consideration that life cycle-based methodologies and in particular LCSA are not fully suitable for dealing with the complexity entailed by SS. The debate on whether 'it is appropriate to expand LCA to include a holistic SA or whether it makes more sense to determine where LCSA fits within a broader SA framework' is probably still at an infant stage and further research is needed to attempt to find an answer.

We do believe that LCSA represents a promising methodology for developing a transparent, robust and comprehensive approach. Nevertheless, mainstreaming of LCT has to be on top of the agenda of LCA experts and ongoing LCSA developments should be in line with the most advanced scientific discussion on sustainability science, attempting to bridge the gaps between the current methodologies for SA. Moreover, the assessment goal should be broadened from avoiding negative impacts, to also proactively enhancing positive impacts, towards the achievement of sustainability goals.

The analysis of the current LCSA frameworks in the context of SS progress, according to the criteria presented in Section 3, and recommendations on how to further develop it are reported in our study (Sala et al. 2012, part II).

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